Finding an optimal district heating market share in 2050 for EU-27: Comparison of modelling approaches

Pia Manz
Fraunhofer Institute for Systems and Innovation Research ISI
Breslauer Straße 48
DE-76139 Karlsruhe
Germany, and
Utrecht University
Princetonlaan 8a, 3584 CS Utrecht
The Netherlands
pia.manz@isi.fraunhofer.de

Şirin Alibaş
Fraunhofer Institute for Systems and Innovation Research ISI
Breslauer Straße 48
DE-76139 Karlsruhe
Germany
sirin.alibas@isi.fraunhofer.de

Tobias Fleiter
Fraunhofer Institute for Systems and Innovation Research ISI
Breslauer Straße 48
DE-76139 Karlsruhe
Germany
tobias.fleiter@isi.fraunhofer.de

Anna Billerbeck
Fraunhofer Institute for Systems and Innovation Research ISI
Breslauer Straße 48
DE-76139 Karlsruhe, and
University of Freiburg
Tennenbacher Str. 4
79106 Freiburg
Germany
anna.billerbeck@isi.fraunhofer.de

Keywords
district heating, energy model, heating, GIS, spatial analysis

Abstract
District heating is an important pillar for decarbonizing the heating of buildings, and is most cost-effective in areas with high heat demands. The lower the heating demand in a certain area, the higher the specific distribution costs of district heating. Furthermore, heat generation for district heating needs to be transformed. All of this affects the costs for the generation and distribution of heat to buildings. The question arises, how a cost-effective share of district heating for the heating of buildings in a future climate-neutral energy system can be quantified.

Existing modelling studies report greatly differing values for the future share of district heating. A better understanding of the reasons for such great differences among studies increases the value and relevance of results. Thereby, we present a review of published system analyses studies that aim to model the future evolution of district heating. Based on this, we conduct a case study, using a high spatial resolution modelling approach to determine the most important parameters for analysing the district heating market share in Germany.

We find in the reviewed studies that the resulting shares for district heating vary greatly, even when similar assumptions are used. Some studies identify possible district heating areas with a high spatial resolution. Furthermore, the modelling approaches for the district heating sector differ by cost assumptions, resulting in different shares for district heating. Nevertheless, modelling is a method to indicate future district heating expansion in different European countries.

Introduction
To limit global warming to about 1.5 °C, the emissions of carbon dioxide and other greenhouse gases (GHG) need to be reduced. Therefore, the European Union committed to a climate-neutral society and economy, i.e. net-zero emissions by 2050 in the Green Deal from 2019 (European Parliament 2020; European Council 2019; European Commission 2019), and developed a long-term strategy and scenarios (European Commission 2018). Even though the building sector reduced their emissions in the last decade (European Environmental Agency 2020), it is a long way to net-zero emissions. Heat supply in particular is heavily dependent on fossil fuels, with a share of 76.8 % in 2018 (Eurostat 2020). Thus, strategies for climate-neutral heating technologies need to be developed. One pillar is the central supply of heat that is distributed to the buildings via the district heating (DH) infrastructure. DH has advantages in densely populated areas, as the additional costs for infrastructure can be offset by lower specific costs for investments in heat generation and lower energy costs.

The building sector follows two main strategies in reaching climate-neutrality: improving the insulation of the building stock and using renewable energy sources to heat the buildings (Levesque et al. 2021). There are many legislations in force in the member states driven by the Energy Performance of Buildings Directive (Directive (EU) 2018/844) to promote energy-efficient insulation and measures for both new and existing buildings. The annual heat demand of a building or a specific area influences the economic competitiveness of different possible heat sources. The main cost factors of heat supply consist of the investments for the generation technology and the costs for fuel and/or electricity. For DH, additional investments for the distribution network, i.e. pipes, are needed. The higher the heat demand of a certain area, the lower the specific distribution costs of DH, thus, DH has the lowest distribution costs in densely populated city centres (Persson and Werner 2011). In a climate-neutral energy system, DH competes with decentralized heating such as individual heat pumps, solar energy, synthetic gases or biomass boilers, with lower generation and distribution costs than the costs for decentralized heat supply to be cost-effective. Besides that, heat generation for DH needs to be transformed, replacing fossil fuel-based supply. Fossil fuels accounted for 63.7 % of the European DH supply in 2018 (Eurostat 2020). In the future, the temperature of the circulating fluid in DH systems can be decreased even below 50 °C, often referred to as 4th generation DH (Lund et al. 2014). A reduced system temperature increases the possibility to utilize more low-temperature excess heat and renewables, while reducing heat losses (Persson and Averfalk 2018) and possibly increasing the competitiveness of DH. The renewable sources can be utilized on a larger scale than decentralised decarbonisation solutions. Electrification is one pillar for decarbonizing DH generation, especially by large heat pumps. Additionally, this could increase the market value of renewables in the electricity sector by providing flexibility on a large scale (Bernath et al. 2021).

These possible transformation pathways lead to changes in cost structures and technological suitability. The development of DH is a country-specific path-dependent process (Gross and Hanna 2019). Energy system models are used to show and evaluate possible pathways and, specifically, their impact on cost-efficient heating supply in different scenarios with incremental changes (Kühnbach et al. 2020). Energy system models are often either simulation models taking into account important drivers and their effects on the relevant energy value with barriers (e.g. demand modelling) or optimization models that minimize overall system costs (e.g. energy system/supply, markets). As district heating infrastructure connects many different aspects in the energy system (heat demand density, cost of supply, infrastructure decisions), existing modelling approaches neglect or greatly simplify at least one of these important parameter.

The question in this paper is how an optimal share of DH for each country can be quantified using energy system models. Optimal is used here in the sense to be a cost-effective market share of DH from the system perspective, so including generation and distribution costs and comparing them to competing technologies for the heating of buildings. The costs for DH include the capital costs (investment) for distribution and generation, as well as operation and maintenance costs and fuel costs, in contrast to individual heating with no distribution costs. We explore how the drivers and dependencies of future development of DH can be captured by models, available data and methodologies, first by a literature review and second by a case study on DH distribution costs. A central parameter used for analyses of modelling results is the DH market share. This is the quantity of energy that is provided by DH in comparison to the amount of energy consumed in residential and service buildings for heating and hot water.

The remainder of the paper is structured as following: We review published system analyses in the second chapter with regard to their results on DH, the level of detail in the modelling and the methodology. In the third chapter, we present a case study for Germany calculating the future distribution costs for DH. In the last two chapters, a synthesis of the different methods and respective model outcomes is carried out and implications on the modelling of DH are concluded.

Literature review

In this section, we present an overview of energy system and buildings studies that were published in the last years. Thereby, only studies that include DH and present climate-neutral or at least 85 % GHG reduction by 2050 or 2070 compared to 1990 are considered and analysed regarding their modelling approach. The geographical focus of our analysis is the EU in the first section, and Germany in the second section. The analysed energy system studies include all sectors. In the third section, an overview of existing model approaches with a focus of buildings or DH modelling are presented. These do not necessarily publish results regarding the other sectors or on national level. Table 1 provides an overview of the different scenarios and studies reviewed in this paper, together with the ambition level of the building stock refurbishment and the technological focus of the scenarios, as lower heat density and thus higher distribution costs or competition by gas grids could influence the results of the DH market share.

EUROPEAN STUDIES

This section summarizes 3 global and 8 European studies, all depicting climate-neutral scenarios for the geographical span that they cover. The lowest DH market shares are found in the scenarios 1.5Tech and 1.5Life, Oeko Vision, and WindEurope PC. In the 1.5 °C scenarios of the EC study, DH keeps the same market share of 2015 in 2050. Although fossil fuels disappear from generation after 2030, the study does not consider geothermal energy or solar thermal energy use for DH (European Commission 2018). The Oeko Vision scenario considers the use of various renewable energies including solar thermal energy in the DH supply. Although the importance of DH networks in "integrating heterogeneous sources of renewable or waste heat" is emphasized; the relatively low share of DH in the market is not explained in detail (Matthes et al. 2018). The WindEurope PC scenario finds constant market shares of DH. The scenario results in relatively high penetration of hydrogen as a heat energy carrier as it argues that the highly flexible renewable electricity can be efficiently transported in the form of hydrogen using the existing gas infrastructure. Therefore, the DH network expansion is not prioritized (Pineda et al. 2018). Scenarios with around 24–30 % market share of DH lie in the middle of the range. All three net-zero GHG emission scenarios of the Net Zero by 2050 study by the ECF have the DH market share in this range (Climact 2018; Keramidas et al. 2018). The most ambitious non-fossil DH potential in the model of the ECF is announced to be 35 % based on the transformational changes, reflecting technical or physical constraints (Climact October 2018). Meanwhile, the highest end of the DH market share range lies at 45 %, found in the Heat Roadmap Europe 4 study (Möller et al. 2019). This potential was quantified via a merit-order approach in local heat supply, where the heat densities and DH distribution costs were explored with high spatial resolution.

Table 1. Scenarios and studies with focus on the EU and Germany.

Study	Type of Study	Scenario Name	Building Stock Efficiency	Focus of the Scenario
EU				
Energy Technology Perspectives (IEA 2020)	Energy system analysis	Sustainable Development Scenario (ETP SDS)	++	Use of a mix of energy carriers
Energy Technology Perspectives (IEA 2017)	Energy system analysis	Beyond 2°C Scenario (B2DS)	++	Use of a mix of energy carriers
World Energy Outlook (IEA 2021)	Energy system analysis	Announced Pledges Scenario (WEO-APS)	+	Moderate use of renewable energy sources
Achieving the Paris Climate Agreement Goals" (Teske 2019)	Energy system analysis	IFS 1.5C	++	Strong use of renewable energy sources
		IFS 2C	+	Moderate use of renewable energy sources
Global Energy and Climate Outlook 2018 by the JRC (Keramidas et al. 2018)	Energy system analysis	GECO 1.5C	++	Strong use of renewable energy sources and electrification
Net Zero by 2050 (Climact 2018a)	Energy system analysis	ECF Technology	++	Strong use of electrification, hydrogen, and CCS
		ECF Demand-Focus	++	Ambitious demand reduction through societal changes
		ECF Shared Effort	+	Moderate demand reduction through societal changes
A Clean Planet for All by the EC (European Commission 2018)	Energy system analysis	1.5Tech	++	Use of a mix of energy carriers
		1.5Life	++	Increased circular economy and sustainable lifestyle changes
The Vision Scenario for the EU by Öko-Institut (Matthes et al. 2018)	Energy system analysis	Oeko Vision	++	Strong use of renewable energy sources
Breaking new ground by (Pineda et al. 2018)	Energy system analysis	WindEurope PC	++	Strong use of renewable energy sources
Low Carbon Energy Observatory by the JRC (Nijs et al. 2018)	Energy system analysis	LCEO Zero Carbon	++	Strong use of renewable energy sources
Heat Roadmap Europe 4 (Paardekooper et al. 2018)	Heating and cooling analysis	Heat Roadmap Scenario	+	Electrification of Heating and Cooling
Hotmaps (Kranzl et al. 2018)	Heating and cooling analysis	Heating and Cooling Scenario Outlook Scenario B	+	Electrification of Heating and Cooling
Germany				
Langfristszenarien 3 (Long-term Scenarios 3) (Consentec et al. 2021)	Energy system analysis	TN-Strom (Climate-neutral Electrification)	++	Strong electrification
		TN-PtG/PtL (Climate-neutral PtG/PtL)	+	Strong use of synthetic fuels
		TN-H2 (Climate-neutral H2)	+	Strong use of hydrogen
Ariadne (Luderer et al. 2021)	Energy system analysis	Elektrifizierung (Electrification)	+	Strong electrification
		E-Fuels	+	Strong use of synthetic fuels
		Wasserstoff (Hydrogen)	++	Strong use of hydrogen
		TechnologieMix (Technology Mix)	+	Use of a mix of energy carriers
Klimapfade 2.0 (Burchardt et al. 2021)	Energy system analysis	KP 2.0	++	Use of a mix of energy carriers
Fraunhofer ISE (Sterchele et al. 2020)	Energy system analysis	Referenz (Reference)	+	Use of a mix of energy carriers

GERMAN STUDIES

In the following, the studies listed in Table 1 with the focus on Germany are reviewed. These studies are often more detailed, using a higher resolution and presenting more in-depth results. The share of DH in the German heat market in 2050 (or 2045 in some studies) varies between 13–37 % among the scenarios of the reviewed studies. In the lower part of the range, up to 19 % DH market share, a mix of scenarios and studies are present: the *Efficiency + PtG* and *Efficiency + HP* scenarios, the *Climate-neutral PtG* and *Climate-neutral H_2* scenarios, both *TM95* and *EL95* scenarios, all Ariadne scenarios modelled by REMIND, and Technology Mix and Hydrogen scenarios modelled by TIMES. The *Efficiency* and *Efficiency + RES* scenarios, the *Climate-neutral Electrification* scenario, Ariadne *Electrification* scenario modelled by both ReMod and TIMES, *Hydrogen* scenario modelled by REMod, and *E-Fuels* scenario by TIMES are in the middle of the range with the DH market share between 20–30 %. Whereas, the *Technology Mix* and *E-Fuels* scenarios of the Ariadne study modelled by REMod result in 32 % DH market share in 2050 in Germany. Lastly, the *Moderate Renovation* and *High Renovation* scenarios of Fraunhofer IEE buildings sector study estimate between 26 % and 37 % DH market share depending on biomass availability.

DH MODELLING APPROACHES

It is seen that the DH market share in 2050 not only varies with scenario assumptions, but also within the same scenarios modelled with different models. Therefore, a comprehensive analysis on the different market shares of DH in different studies must also include the difference in DH modelling approaches. Table 2 summarizes the models reviewed in this paper presenting the cost factors they include as well as the spatial resolution, if any of these factors are reported.

On European level, there are several projects that analyse the heating and cooling sector with high spatial resolution and develop decarbonisation scenarios. In these studies, one important parameter is the heat density in GJ/m^2, i.e. the demand for heating and sanitary hot water for buildings, related to the land area. In DH system planning, the linear heat density in GJ/m is an important parameter for evaluating costs and heat losses. It is the quotient of the annual sold heat and of the trench length of the DH pipe system. The trench length is difficult to determine for future DH systems, especially on European level. Thus, methodologies mostly use empirical correlations of other parameters to the linear heat density. This central methodological approach was first introduced by (Persson and Werner 2011) and was further developed in the studies described in the following.

In the study Heat Roadmap Europe 2 (Connolly et al. 2014), the authors assume an extension of DH in the EU up to a 50 % share for residential and service buildings in 2050 for an 80 % CO_2-reduction. This was based on a detailed Geographical Information System (GIS) analysis. Until that time, the potential of DH was rarely analysed and instead assumed to be constant at current levels. In the updated Heat Roadmap 4 study (Paardekooper et al. 2018; Möller et al. 2019), distribution costs are based on the heat density. A DH market share of 45 % is deemed feasible with average distribution costs of €3/GJ for the 14 core countries of the analysis, together with moderate refurbishment measures. This share corresponds to the heat demand in the heat density categories “dense” and “very dense”. In the ongoing project sEEnergies, this described approach for the distribution costs was refined regarding cost data and extended to include service pipes (Persson et al. 2021). For the open-source tool Hotmaps (Kranzl et al. 2018) the methodology was adapted in the study of (Fallahnejad et al. 2018), calculating the distribution costs for DH on a high resolution of 100x100m. First, distribution costs are calculated in dependence of input parameters. This is then compared with heat saving costs for buildings with the model INVERT, but without analysing the supply costs for DH (Hummel et al. 2021). They vary the grid cost ceiling as maximum costs for distribution and transmission costs. Additionally, the highest heating demand served by DH from the start until the end year of investment is considered, hence, the maximum needed capacity for the distribution pipes. The connection of areas with transmission lines in optimized. The maximum grid cost ceilings are around €2.2 to 4.7/GJ (€8 to 17/MWh). In the scenario, the DH market share reaches 14 % in the ambitious scenario with a decrease of the heating demand by -35 %. The spatial approach was compared in (Fallahnejad 9/21/2021), with detailed infrastructure optimization model on pipe level, with the conclusion that similar result patterns can be achieved. This method was used for Austria by (Kranzl et al. 9/21/2021), and includes costs for DH supply and different scenarios on heat savings. A cost-effective share was defined by comparing the costs for DH supply with decentralized supply for all possible DH areas identified. With ambitious renovation, the maximum share ranges from 12 to 52 % for distribution costs of €8 to 14/GJ (€30–50/MWh). The connection rate was varied also from 45 % to 90 %, reaching the high levels of DH market shares only with a very high connection rate.

The model GEMOD, which was used for some of the German studies analysed above, uses another approach in contrast to the approaches described above. It analyses the building stock with a resolution of 500x500m and considers for different region typologies several costs somponents. Furthermore, the model considers existing DH systems and investments that are already made (ifeu et al. 2019). The detailed buildings sector study of Fraunhofer IEE builds on GEMOD and additionally announces the use of different connection rates depending on the topology of the residence area. In urban DH grids, the connection rate is considered to be 60 %; while in rural DH grids, the connection rate is 70 %, with marginal grid costs of €10/GJ (€35/MWh) and €14/GJ (€50/MWh), respectively (Gerhardt et al. 2019).

RESULTS OF THE LITERATURE REVIEW

In Figure 1, the heating demand supplied by DH compared to the total heating demand of buildings (DH market share) is depicted, with each data point representing one scenario by a European (on the left) or German (on the right) study. Tthe annual renovation rate for buildings is shown on the abscissa, as we expect with increasing renovation rate, and thus, decreasing heat density, the share of DH in the scenarios decreases. If no renovation rate was reported, it was estimated from energy savings in the building sector as an indication. Additionally, the scenarios are characterized by their technological pathways, if possible, and by the level of DH modelling detail. In principal, the technological focus of the scenarios can be differed by

Table 2. Overview of existing literature and models for climate-neutral scenarios considered in the analysis.

Study/Model	Cost Factors considered in DH modelling	Spatial Resolution for DH modelling
Heat Roadmap Europe 4 (Persson et al. 2019)	DH distribution costs are analysed regarding heat density, average distribution costs of 3 €/GJ feasible	100x100m
Hotmaps (HotMaps 2016 - 2020)	DH distribution costs are analysed regarding heat density, set maximum grid ceilings of up to 4.7 €/GJ	100x100m
LFS3 & Agora – GEMOD (Consentec et al. 2021), (ifeu et al. 2019)	Heat generation, pumping, distribution, delivery station, monitoring, and overhead costs. Supply costs from supply model. Cost ceiling for heat and generation of heat as well as min. sales heat density defined per urban and rural heat networks.	500 x 500m. Database on existing DH systems (66.8 TWh)
Fraunhofer IEE – own calculations built on GEMOD (Gerhardt et al. 2019)	Distribution costs per densification of existing networks or new networks. Min. heat density for urban and rural heat networks. Cost ceiling for heat and generation of heat.	GIS-based dataset for 2030, classification by settlement categories
Fraunhofer ISE & Ariadne – REMod (Sterchele et al. 2020), (Luderer et al. 2021)	Cost of connection defined [€/kWhth].	Integrated energy system optimization model, national resolution.
BDI – own calculations (Burchardt et al. 2021)	Different acquisition costs for single and family houses (3550€ and 3730€, respectively.)	No specification regarding regional resolution.
DENA – own model for buildings, DIMENSION+ (dena 2017)	12 ct/kWh in 2030, 14 ct/ kWh in 2045 (brutto).	No specification regarding regional resolution.

level of electrification and the availability of hydrogen or carbon-based synthetic gases produced by Power-to-Gas (PtG). The scenarios are categorized as "detailed modelling" when the DH modelling was on higher geographical resolution than national level.

The DH market shares differ a lot between the scenarios. The results for Germany trend to be more robust and to a higher share of DH and lower renovation rates than the European studies. The compared scenarios do not show a relation of renovation rates and DH market shares. In fact, the European studies show a DH market share higher than 15 % with renovation rates above 2 %. Additionally, the technology focus does not seem to influence the share of DH. Scenarios based on detailed modelling approaches show more converging results regarding the technology focus, but not regarding the renovation rates. Availability of PtG or hydrogen lead to lower DH market shares up to 17 %. In electrification scenarios, the highest market shares are reached, up to 37 % (Germany) and 45 % (EU).

The differences of market shares for DH within different scenarios of the same study are often small when the same model is used, leading to the conclusion that most models do not consider the influencing parameters for DH extension. Especially assumptions on the connection rate are mostly not reported, and it is unclear whether these studies consider a 100 % connection rate when calculation the costs. Similarly, costs for the generation of DH are mostly not reported, e.g. by the levelised costs of heat. Comparing the cost structure of DH to individual heating, the studies come to different conclusions. Not only the distribution costs need to be considered, but also future energy costs. In general, DH is competitive if the levelised costs for DH supplied to the end-consumer is lower than the local, individual heating case. The study of (Persson et al. 2019) assumes €20/GJ for local heat generation, and distribution costs up to €10/GJ for sparsely populated areas. The study of (Kranzl et al. 9/21/2021) also consider distribution costs in the magnitude of €10/GJ as competitive. In (Gerhardt et al. 2019), marginal costs for distribution are assumed at €14/GJ (€50/MWh) in urban areas.

Case study

For Germany, we analyse and estimate the distribution costs for future DH development for the years 2020, 2030 and 2050 with our own GIS-based modelling approach. The calculation of the distribution costs is based on (Persson and Werner 2011). The costs that are associated with the distribution infrastructure are analysed regarding varying DH market shares and connection rates.

METHODOLOGY AND DATA

We combine two models and methodological steps: First, the building stock evolution is modelled until 2050 in annual steps on national level with the model FORECAST. The model FORECAST is a bottom-up demand simulation model for the demand sectors industry and buildings (Fleiter et al. 2018). Input data are, among others, energy prices, policy instruments and cost data for technologies. The building stock modelling considers the floor area per building category (sector, type, construction age, refurbishment status) and refurbishment measures that increase the efficiency of the building envelope.

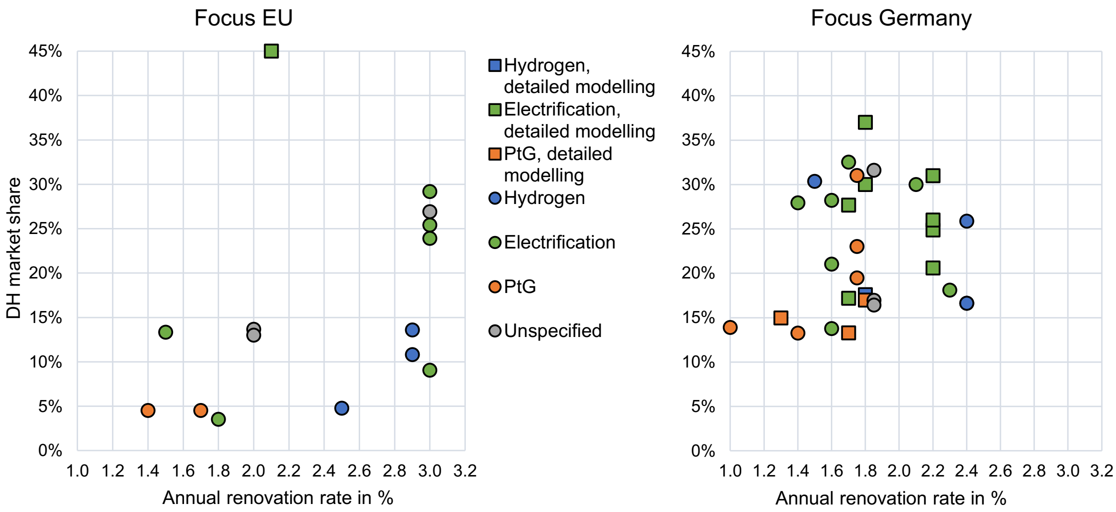

Figure 1. Study overview by the characteristics annual renovation rate, DH share of total heat market and scenario focus technologies in the modelling end year (2045, 2050 or 2070) with the context of EU (left) and Germany (right). Own illustration.

The resulting floor area per building category and its respective specific annual energy demand in GJ/m² is the used output of the model. Second, the spatial distribution of energy demand for heating of buildings is analysed and distribution costs are calculated. The results from the first step are input data in the second step to assess the spatial energy demand for space heating and hot water on hectare level in the software QGIS with the PyQGIS plugin. For each hectare, the floor area per building category is modelled for the status quo and calibrated on national level with the FORECAST data. Refurbishment measures until 2050 are distributed spatially depending on the existing building stock and statistical data. With this dataset and geographical layers, the energy demand for heating of buildings (including sanitary hot water) is modelled per hectare for future years. Based on the energy demand, the costs associated to the distribution of heat are modelled with the approach presented by the study of (Persson et al. 2019) and adapted in (Greif 2021). The marginal distribution capital costs (MDCC) C_d, which is the annuitized payback on investment capital for the distribution pipes, are assessed with following formula:

$$C_d = \frac{a\cdot(C_1+C_2\cdot d_a)}{q_L\cdot w},$$

with a=0.051 as the annuity factor with 30 years and 3 % interest rate, C_1=€212/m² as the construction cost constant and C_2=€4464/m as the construction cost coefficient, da=0.0486·ln $(q_L\cdot w)$+0.0007, as the average pipe diameter in m, $q_L = \frac{Q_S}{A_L}$ as the heat density in GJ/m² per year in the considered land area of one hectare, w=0-60 m, as the effective width depending on the plot ratio $e = \frac{A_B}{A_L}$. For each cell with the size of 100x100m, the heat density q_L in GJ/m² and the plot ratio e (floor area A_B divided by the land area of one hectare A_L) is calculated for the analysed years. With that, the marginal distribution capital costs C_d are calculated per hectare. The MDCC are calculated for different DH market shares. As current connection rates are rather typically around 30 %, the connection rate is varied as well.

The most important data sources for the regional datasets are the floor area per construction period and sector as well as the population from the Hotmaps open data repository (Pezzutto et al. 2019), visualized online (HotMaps 2016 - 2020). The data were compared to the census data from 2011 (Statistische Ämter des Bundes und der Länder 2021) and calibrated to the national statistics of floor area. Furthermore, the German Kreditanstalt für Wiederaufbau (KfW) publishes the subsidies for energy-efficient building renovation. In the most recent annual funding report (KfW Bankengruppe 2020), the funding for different categories is reported on NUTS 3[1] level. From that, economic indicators are extracted that signify the economic activity for building refurbishment in the residential and tertiary sector. The scenario for the building renovation was based on an ambitious scenario for renovation depth, and moderate renovation rate of averaged 1.7 % per year.

RESULTS OF THE CASE STUDY

The resulting layers are in the data format of tiff-layers, which store the values for each cell as a raster file. The values are the marginal distribution capital costs in €/GJ of energy served. There is one layer for each variation of the total market share and connection rate. In Figure 2, the resulting raster layers with the corresponding MDCC are shown exemplary for the city of Karlsruhe, located in the South of Germany. The densely populated city centre with a high heat density has the lowest specific distribution costs. The suburban and more rural areas in the surrounding have increasing costs. The variation of the national DH market share and connection rate show how the served area increases with decreasing rates, with higher distribution costs of more than €10/GJ. The map with a market share of 20 % show that the DH area could be quite small and concentrated in the city centre when all buildings are connected to DH (100 % connection rate). If a lower connection rate is assumed, the DH area increases to reach a DH market share of 20 %. The same applies to a market share of 40 %, but the effects

1. NUTS: The NUTS classification (Nomenclature of territorial units for statistics) is a hierarchical system for dividing up the economic territory of the EU.

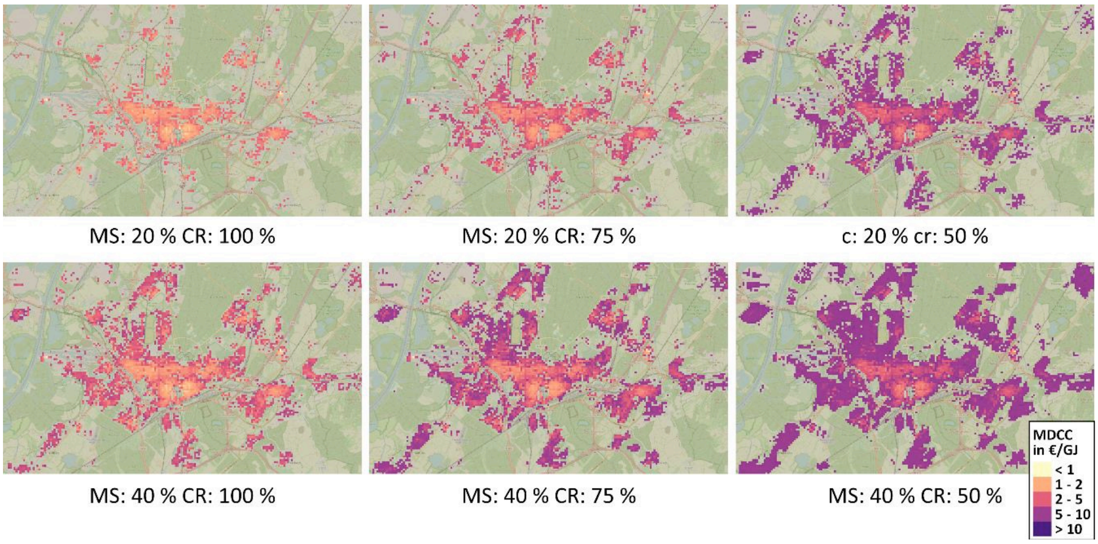

Figure 2. Marginal distribution capital costs for DH market shares (MS) of 20 % and 40 % and connection rates (CR) of 100 %, 75 % and 50 % for the year 2050 for the example of Karlsruhe. Own illustration.

are more distinct, and almost all suburban areas are connected to the DH grid, with substantial higher distribution costs that are not competitive. This modelling shows, that the connection rate is a main parameter to reach high DH market shares with low distribution costs. With connection rates below 50 % in the future, a DH market share of 20 % results in outstretched DH grids with high distribution costs up to €10/GJ.

In Figure 3, the cumulated distribution capital costs are shown for the years 2020, 2030 and 2050. For each cell where DH is being installed, the costs for each year are analysed. The distribution costs increase with lower heating demands in general, which is the reason for higher costs in future years. The MDCC are steep, almost linear increase for all years. The ADCCs have rather a wide range from about 20 to 40 % market share where the costs do not increase as much as for achieving higher market shares. The influence of the connection rate is pronounced, with about four times higher ADCC when comparing connection rates of 100 % to 50 %. With assumed feasible ADCC of €4/GJ, a DH market share of 30 % in 2050 can be reached in Germany, but only with the assumption of all buildings being connected to the DH grid. A lower connection rate of 75 % or 50 % leads to a possible market share of 12 % and 4 %, respectively.

The case study shows that a high spatial resolution is needed for cost assessment that is related to DH extension, to include parameters of heat density and connection rates. The connection rate within the modelled DH areas is a very important parameter. The methodology is similar to the approach first presented by (Persson and Werner 2011), refined in (Persson et al. 2019) and adapted and extended in (Fallahnejad et al. 2018). Compared to (Persson et al. 2019), the resulting distribution cost curves differ for the example of Germany, as they found a market share of 56 % with average distribution capital costs of €2.9/GJ. In the case study, market shares of 23 % and 16 % for the years 2020 and respectively 2050 could be found with this cost limit. The assumed cost ceiling (MDCC) of 2.2 to €4.7/GJ by (Fallahnejad et al. 2018) is in the same range, reaching a DH market share of up to 90 % for the case of Vienna, with a connection rate of 90 % and low heat savings, while a connection rate of 60 % and high heat savings lead to a DH market share of 50 %. This example of a city shows similar results to the case of Karlsruhe, where costs below €5/GJ are reached for all configurations in the urban areas.

Discussion

Limitations of the presented case study, as well as of most other studies, are that today's state of DH market share of around 12 % and its corresponding investments already made are not considered. The study of (Sterchele et al. 2020) considers different costs for existing and new DH systems. However, a complete overview of current DH systems in Europe does not exist. Furthermore, lower system temperatures in the DH grids affect the distribution costs as lower insulation is needed and the pipe diameter potentially need to be wider, depending on the development of the specific heat demand per area. These effects are uncertain.

In summary, there are only a few European energy system models that consider distribution costs and connection rates within DH areas. Models with a national resolution are not sufficient to capture the dependencies of the DH infrastructure with demand and supply evolution. Analysing the potential and cost-optimal share of DH in a climate-neutral energy system, several factors have to be considered. First, the costs are variable depending on the DH market share. The higher the market share of DH, the more areas with low heat density are connected, thus the distribution costs increase. Second, with higher the connection rate within the DH areas, the distribution costs decrease, which could be shown by the models with high spatial resolution and the case study in this paper. Additionally, the DH supply costs depend on the DH market share, and also influence the economic feasibility of DH. This shows, that DH modelling is dependent on the evolution of the energy demand (often covered by simulation models) and the supply (often by optimization models) and necessitates integrated modelling or iterations. In most studies, the modelling approach is not documented completely, and to what extend these interdependencies are integrated. High spatial resolution of the models leads to more converging results, as it could be observed for studies with German context. Addition-

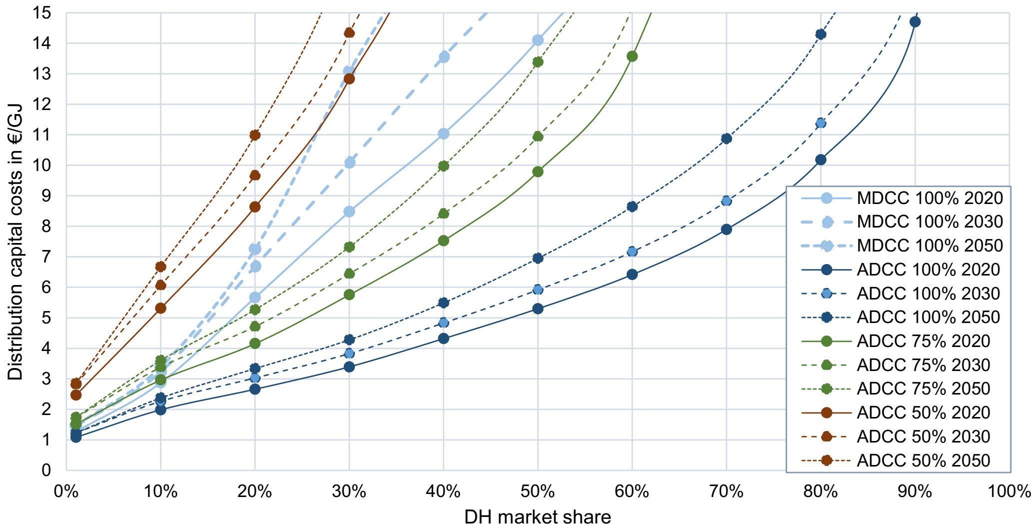

Figure 3. Marginal (MDCC) and average distribution capital costs (ADCC) for different market shares and connection rates of 100 %, 75 % and 50 % for district heating in the buildings sector in Germany in the years 2020, 2030 and 2050. Own illustration.

ally, the studies with high spatial resolution are more conservative regarding the DH market share for the German context, which may be due to more specific knowledge about barriers. The marginal distribution costs assumed in the reviewed studies and in the case study that lead to a competitive DH market share (up to €10/GJ) lie in the similar range. However, it could be shown that the connection rate is a decisive parameter and should be reported together with the results. Increasing the connection rate within DH areas is a substantial factor to decrease the distribution costs, which is shown by the literature and the presented case study. Finally, especially for EU studies, many input data with high spatial resolution are needed. There are online repositories and open data sets, some currently under development, which are a great source for further modelling activities and regional stakeholders. Nevertheless, regarding the modelling of DH, comprehensive datasets about the costs and prices of DH, existing DH grids and building stock data with a high spatial resolution are so far not available.

Conclusions and Outlook

A future cost-effective, optimal market share of DH in the European energy system for the provision of heat to buildings was not clearly stated by any of the study analysed in this paper. Models with a high spatial resolution and a good database are needed. The results on published DH market shares are not sensitive on the assumed ambition level of refurbishments of buildings. The future DH market share in the models lies between 5 to 45% in the EU, and between 13–37 % in Germany. The literature research shows, that with higher modelling detail the results tend to converge. Still, the range of results makes the modelling results difficult to interpret for policy makers. Summarized, it can be stated that all studies include at least a certain share of DH. The scenarios and studies show that DH grids are most competitive in urban areas with the highest heating densities and thus, the lowest distribution costs and therefore should be prioritized over (new) gas distribution grids in urban areas. Especially in dense city centres, DH could be the only option for renewable heat supply for non-refurbished buildings. The more buildings are connected to the DH grid within one area (connection rate), the lower the costs are. DH allows to include vast renewable potentials with a high efficiency and excess heat potentials, whereas the energy sources for individual heating are limited. As the installation and extension of DH infrastructure has high investment costs, investment security should be ensured at least for certain areas.

In general, policies towards a climate-neutral energy system should avoid path dependencies and lock-in effects for non-cost-optimal technologies. This is especially true for DH, as infrastructure development necessitates high investments. Policies to increase the connection rates are important to decrease the distribution costs and should include regulatory frameworks with connection obligations in specific areas or financial support measures for end-users that want to connect to DH networks. Furthermore, policies are needed to increase the efficiency in existing high-temperature grids like lowering system temperatures. The most important measure is to increase the DH share especially in city centres e.g. by instruments such as customer participation, through ownership structures or financial participation. These can address the barrier of high investments costs and the needed investment security.

Refining the modelling approaches for energy system analysis and DH development is important for concluding policy recommendations. Future costs and prices for DH supply and distribution are an important parameter while being highly uncertain. This limit of modelling should be considered when interpreting the results. The installation and extension of DH infrastructure is dependent on regional stakeholders, with individual visions and opinions. Policies for harmonising the differing interests and for including all relevant stakeholders can be for example strategic regional heat planning activities. Indicating a robust country-specific feasible share of DH by energy system models and findings on economic feasibility of DH can help to derive and evaluate the needed policies for reaching climate-neutral heat supply.

References

Bernath, Christiane; Deac, Gerda; Sensfuß, Frank (2021): Impact of sector coupling on the market value of renewable energies – A model-based scenario analysis. In Applied Energy 281, p. 115985. DOI: 10.1016/j.apenergy.2020.115985.

Burchardt, J.; Franke, K.; Herhold, P.; Hohaus, M.; Humpert, H.; Päivärinta, J. et al. (2021): Klimapfade 2.0. Ein Wirtschaftsprogramm für Klima und Zukunft. Boston Consulting Group.

Climact (2018): Net Zero by 2050: From whether to how. Zero emissions pathways to the Europe we want. A report commissioned by the European Climate Foundation.

Climact (2018): 2050 scenario analysis using the EU CTI 2050 Roadmap Tool. BUILDINGS sector. Climact; European Climate Foundation; Climate Works Foundation, October 2018. Available online at https://europeanclimate.org/wp-content/uploads/2019/11/09-18-2050-scenario-analysis-using-the-eu-cti-2050-roadmap-tool-buildings-sector.pdf, checked on 3/14/2022.

Connolly, D.; Lund, H.; Mathiesen, B. V.; Werner, S.; Möller, B.; Persson, U. et al. (2014): Heat Roadmap Europe. Combining district heating with heat savings to decarbonise the EU energy system. In Energy Policy 65, pp. 475–489. DOI: 10.1016/j.enpol.2013.10.035.

Consentec; Fraunhofer ISI; TU Berlin; ifeu (2021): Langfristszenarien für die Transformation des Energiesystems in Deutschland 3. Treibhausgasneutrale Hauptszenarien Modul Gebäude.

dena (2017): Gebäudestudie. Szenarien für eine marktwirtschaftliche Klima- und Ressourcenschutzpolitik 2050 im Gebäudesektor. Eine Studie der dena, der geea und weiterer Verbände aus dem Bereich Gebäudeenergieeffizienz. Deutsche Energie-Agentur. Berlin.

European Commission (2018): A Clean Planet for all. A European long-term strategic vision for a prosperous, modern, competitive and climate neutral economy. In-Depth analysis in support of the Commission Communication COM(2018) 773.

European Commission (2019): The European Green Deal. Communication from the Commission to the European Parliament, the European Council, the European Economic and Social Committee and the Committee of the Regions (COM(2019) 640 final). Available online at https://eur-lex.europa.eu/resource.html?uri=cellar:b828d165-1c22-11ea-8c1f-01aa75ed71a1.0002.02/DOC_1&format=PDF, checked on 1/19/2021.

European Council (2019): European Council meeting (12 December 2019) - Conclusions. In EUCO 29/19. Available online at https://www.consilium.europa.eu/media/41768/12-euco-final-conclusions-en.pdf, checked on 1/19/2021.

European Environmental Agency (2020): EU's 2020 GHG inventory submission under the UNFCCC. Data Viewer. Available online at https://www.eea.europa.eu/ds_resolveuid/f4269fac-662f-4ba0-a416-c25373823292, checked on 1/19/2021.

European Parliament (2020): The European Green Deal. European Parliament resolution of 15 January 2020 on the European Green Deal (2019/2956 (RSP)). In P9_TA(2020)0005. Available online at https://www.europarl.europa.eu/doceo/document/TA-9-2020-0005_EN.pdf, checked on 1/19/2021.

Eurostat (2020): Complete energy balances (nrg_bal_c). Available online at https://ec.europa.eu/eurostat/data/database, checked on 7/15/2020.

Fallahnejad, Mostafa (2021): District heating distribution grid costs: a comparison of two approaches. 7th International Conference on Smart Energy Systems, 9/21/2021.

Fallahnejad, Mostafa; Hartner, Michael; Kranzl, Lukas; Fritz, Sara (2018): Impact of distribution and transmission investment costs of district heating systems on district heating potential. In Energy Procedia 149, pp. 141–150. DOI: 10.1016/j.egypro.2018.08.178.

Fleiter, Tobias; Rehfeldt, Matthias; Herbst, Andrea; Elsland, Rainer; Klingler, Anna-Lena; Manz, Pia; Eidelloth, Stefan (2018): A methodology for bottom-up modelling of energy transitions in the industry sector: The FORECAST model. In Energy Strategy Reviews 22, pp. 237–254. DOI: 10.1016/j.esr.2018.09.005.

Gerhardt, Norman; Ganal, Irina; Jentsch, Mareike; Rodriguez, Juan; Stroh, Kilian; Buchmann, Eisabeth Klara (2019): Entwicklung der Gebäudewärme und Rückkopplung mit dem Energiesystem in -95 % THG-Klimazielszenarien. Teilbericht. Fraunhofer-Institut für Energiewirtschaft und Energiesystemtechnik IEE (Fraunhofer IEE).

Greif, Lukas (2021): Modelling of district heating potentials in Germany. Master's Thesis. Karlsruhe Institut für Technologie.

Gross, Robert; Hanna, Richard (2019): Path dependency in provision of domestic heating. In Nat Energy 4 (5), pp. 358–364. DOI: 10.1038/s41560-019-0383-5.

HotMaps (2016 - 2020): Hotmaps Toolbox. The open source mapping and planning tool for heating and cooling: EU Horizon 2020 research and innovation program under grant agreement No. 723677. 2016–2020. Available online at https://www.hotmaps.eu, checked on 8/19/2021.

Hummel, M.; Büchele, R.; Müller, A.; Aichinger, E.; Steinbach, J.; Kranzl, L. et al. (2021): The costs and potentials for heat savings in buildings: Refurbishment costs and heat saving cost curves for 6 countries in Europe. In Energy and Buildings 231, p. 110454. DOI: 10.1016/j.enbuild.2020.110454.

IEA (2017): Energy Technology Perspectives 2017. Catalysing Energy Technology Transformations. International Energy Agency.

IEA (2020): Energy Technology Perspectives 2020. International Energy Agency.

IEA (2021): World Energy Outlook 2021. International Energy Agency.

ifeu; Fraunhofer IEE; Consentec (2019): Building sector Efficiency: A crucial Component of the Energy Transition. A study commissioned by Agora Energiewende. Berlin.

Keramidas, Kimon; Tchung-Ming, Stéphane; Diaz Vazquez, Ana; Weitzel, Matthias; Vandyck, Toon; Després, Jacques et al. (2018): Global Energy and Climate Outlook 2018: Sectoral mitigation options towards a low-emissions economy. Global context to the EU strategy for long-term greenhouse gas emissions reduction. Luxembourg: Publications Office of the European Union (JRC science for policy report, 2018).

KfW Bankengruppe (2020): Förderreport KfW Bankengruppe. Stichtag: 31. Dezember 2020. Available online at https://www.kfw.de/Presse-Newsroom/Pressematerial/Förderreport/KfW-Förderreport_2020.pdf.pdf, checked on 1/14/2022.

Kranzl, Lukas; Fallahnejad, Mostafa; Hasani, Jeton; Hummel, Marcus; Schmidinger, David (2021): The economic potential of district heating under climate neutrality: the case of Austria. 7th International Conference on Smart Energy Systems, 9/21/2021.

Kranzl, Lukas; Hartner, Michael; Müller, Andreas; Resch, Gustav; Fritz, Sara; Fleiter, Tobias et al. (2018): Heating & Cooling outlook until 2050, EU-28. Hotmaps Report D5.2 Hotmaps - Heating and Cooling Open Source Tool for Mapping and Planning of Energy Systems.

Kühnbach, Matthias; Guthoff, Felix; Bekk, Anke; Eltrop, Ludger (2020): Development of Scenarios for a Multi-Model System Analysis Based on the Example of a Cellular Energy System. In Energies 13 (4), p. 773. DOI: 10.3390/en13040773.

Levesque, Antoine; Pietzcker, Robert C.; Baumstark, Lavinia; Luderer, Gunnar (2021): Deep decarbonisation of buildings energy services through demand and supply transformations in a 1.5°C scenario. In Environ. Res. Lett. 16 (5), p. 54071. DOI: 10.1088/1748-9326/abdf07.

Luderer, Gunnar; Kost, Christoph; Dominika (2021): Deutschland auf dem Weg zur Klimaneutralität 2045. Szenarien und Pfade im Modellvergleich: Potsdam Institute for Climate Impact Research.

Lund, Henrik; Werner, Sven; Wiltshire, Robin; Svendsen, Svend; Thorsen, Jan Eric; Hvelplund, Frede; Mathiesen, Brian Vad (2014): 4th Generation District Heating (4GDH). In Energy 68, pp. 1–11. DOI: 10.1016/j.energy.2014.02.089.

Matthes, Felix Chr.; Blanck, Ruth; Greiner, Benjamin; Zimmer, Wiebke; Cook, Vanessa (2018): The Vision Scenario for the European Union. 2017 Update for the EU-28. Öko-Institut e. V. Berlin.

Möller, Bernd; Wiechers, Eva; Persson, Urban; Grundahl, Lars; Lund, Rasmus Søgaard; Mathiesen, Brian Vad (2019): Heat Roadmap Europe: Towards EU-Wide, local heat supply strategies. In Energy 177, pp. 554–564. DOI: 10.1016/j.energy.2019.04.098.

Nijs, W.; Ruiz Castello, P.; Tarvydas, D.; Tsiropoulos, I.; Zucker, A. (2018): Deployment Scenarios for Low Carbon Energy Technologies. Deliverable D4.7 for the Low Carbon Energy Observatory (LCEO). Joint Research Center. Publications Office of the European Union, Luxembourg.

Paardekooper, Susana; Lund, Rasmus; Mathiesen, B. V.; Chang, Miguel; Petersen, Uni Reinert; Grundahl, Lars et al. (2018): Heat Roadmap Europe 4: Quantifying the Impact of Low-Carbon Heating and Cooling Roadmaps. Aalborg Universitetsforlag.

Persson, Urban; Averfalk, Helge (2018): Accessible urban waste heat. Deliverable D1.4 ReUseHeat. Recovery of Urban Excess Heat. Available online at https://www.reuseheat.eu/wp-content/uploads/2019/02/D1.4-Accessible-urban-waste-heat.pdf, checked on 9/14/2020.

Persson, Urban; Möller, Bernd; Sánchez-García, Luis; Wiechers, Eva (2021): District heating investment costs and allocation of local resources for EU28 in 2030 and 2050. sEEnergies Report D4.5 – Quantification of Synergies between Energy Efficiency First Principle and Renewable Energy Systems. Available online at https://www.seenergies.eu/reports/

Persson, Urban; Werner, Sven (2011): Heat distribution and the future competitiveness of district heating. In Applied Energy 88 (3), pp. 568–576. DOI: 10.1016/j.apenergy.2010.09.020.

Persson, Urban; Wiechers, Eva; Möller, Bernd; Werner, Sven (2019): Heat Roadmap Europe: Heat distribution costs. In Energy 176, pp. 604–622. DOI: 10.1016/j.energy.2019.03.189.

Pezzutto, Simon; Zambotti, Stefano; Croce, Silvia; Zambelli, Pietro; Garegnani, Giulia; Scaramuzzino, Chiara et al. (2019): WP2 report – Open Data Set for the EU28. Hotmaps Report D2.3 Hotmaps – Heating and Cooling Open Source Tool for Mapping and Planning of Energy Systems.

Pineda, Ivan; Fraile, Daniel; Tardieu, Pierre (2018): Breaking new ground. Wind energy and the Electrification of Europe's Energy System. WindEurope.

Statistische Ämter des Bundes und der Länder (2021): Regionalstatistik 31211-03-01-5-B. Gebäude mit Wohnraum nach Baujahr - Stichtag 09.05.2011 regionale Tiefe: regionale Ebenen. Available online at https://www.regionalstatistik.de/genesis//online?operation=table&code=31211-03-01-5-B, checked on 9/15/2021

Sterchele, Philip; Brandes, Julian; Heilig, Judith; Wrede, Daniel; Kost, Christoph; Schlegl, Thomas et al. (2020): Wege zu einem klimaneutralen Energiesystem. Die deutsche Energiewende im Kontext gesellschaftlicher Verhaltensweisen. Fraunhofer-Institut für Solare Energiesysteme ISE. Freiburg.

Teske, Sven (2019): Achieving the Paris Climate Agreement Goals. Global and Regional 100 % Renewable Energy Scenarios with Non-energy GHG Pathways for +1.5 °C and +2 °C. Cham: Springer International Publishing.

Acknowledgements

We would like to thank Lukas Greif for his valuable contribution to the development of the regional database and the GIS model. This work was financially supported by the German Federal Ministry for Economic Affairs and Energy Germany within the research project VerSEAS, grant number 03EI1018C.